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This paper appears in: **Vehicular Technology Conference Proceedings, 2000. VTC 2000-Spring Tokyo. 2000 IEEE 51st**
05/15/2000 -05/18/2000, 2000
Location: Tokyo , Japan
On page(s): 1318-1322 vol.2
Volume: 2, 2000
References Cited: 15
IEEE Catalog Number: 00CH37026
Number of Pages: 3 vol. (lvi+2577)
INSPEC Accession Number: 6678164

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Index Terms:
access protocols adaptive antenna arrays array signal processing cellular radio mobile antennas network topology packet radio networks AD-ALOHA protocol MAC layer adaptive beamforming adaptive protocol architecture cellular networks mobile adaptive antennas mobile stations multi-hop packet radio networks network performance network topology simulation

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Performance of Multi-hop Packet Radio Networks with Mobile Adaptive Antennas*

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Abstract - Adaptive antenna technology is now regarded as one of the hot-point research areas in mobile communications. However, its applications on the mobile stations receive little attentions. This paper considers the performance of a multi-hop packet radio network employing adaptive antennas at the mobile stations. A simple adaptive beam-forming policy is presented. Analysis and simulation indicates that mobile stations in packet radio networks employing mobile adaptive antennas can offer a significant performance enhancement when compared with their omnidirectional counterparts. In addition, an AD-ALOHA protocol for MAC layer and the adaptive protocol architecture with adaptive antenna technology were proposed.

1. Introduction

Adaptive antenna is now regarded as one of the key system components in future generation cellular networks[1-3]. However, research considering adaptive antennas has been largely focused towards its utilization in the base station of cell operational environments. As such, due to the large size and the complicated technology of adaptive antennas, the application of this technology to mobile stations receives little attention. Commercial wireless communication systems currently do not employ smart antenna structures at mobile stations. Recently, some new techniques enable several antenna elements to be placed in a small package, which make it possible to be used in mobile stations[4-6]. Providing interference rejecting, fading mitigation, and battery power saving for mobile stations, such techniques will be immediate interest to commercial and military manufacturers.

Packet radio networks can provide wireless communication and data distribution among mobile terminals where the omnidirectional antennas are often used. Because mobile stations are common handset or vehicular, the limitation of the height of antennas (often less than 2 meter) and the battery power not only limit the transmission distance but also make it often suffer from fading, multipath, shadows, near far effect and jamming. The mobility of the radios and the variability of the propagation and interference on the links result in a highly dynamic topology for the network, which make the protocols for the networks very complex and inefficiency. Fortunately, adaptive antenna can solve this problem perfectly, and its use has a profound influence on the low layer design of networks. In order to take full advantages of mobile adaptive antennas, adaptive protocol architecture based on adaptive antenna technology must be designed. This has become an urgent research work. However, research focused on this has not been seen in any papers.

This paper introduces adaptive antenna technology to multihop PRNET and simulates its influence on the performance of the network. A simple digital beam-forming policy is used, which can be easily implemented in the small mobile adaptive antennas. In addition, the mode control strategies of adaptive antennas and adaptive network protocols are further discussed.

2. Adaptive Antenna and Networks Model

2.1 Mobile Adaptive Antenna Model

The type of mobile adaptive antenna that is considered here is an antenna array that is capable of modifying its radiation pattern and other parameters by means of internal feedback control while the antenna system is operating. Usually, the received signal from each antenna element of the array is multiplied by a weight (a complex quantity consisting of an amplitude and a phase) and summed up to yield the output. The weights are controlled by an adaptive algorithm (LSCMA[7], BSCMA[8] etc.) such that the system can learn the unknown or time-varying radio environment and adapt itself. This permits the maximization of the signal-to-noise ratio of some desired signal that is received in the presence of noise and interference, at the receiver output. Realization of such an antenna concept has recently become feasible with state-of-art Digital Beam Formers (DBF). Due to the limitation of size and weight, the adaptive antenna of mobile stations can not be sophisticatedly implemented. Furthermore, packet radios operate in half-duplex and single channel, which makes the structure and the functions of the mobile adaptive antenna can be much simple than those of base stations in cellular networks.

In our discussion, the adaptive antenna has two operational modes. One is omnidirectional(o), another

* Supported by NSF of China (69872028)

is directional(d). Former is the default mode that has the same performance with the traditional omnidirectional antenna. In particular for the case of adaptive antennas in mobile stations, ray-tracing is most beneficial because it can only provide the impulse response of the radio channel, but it can also provide the site dependent information in term of the Angel of Arrival (AOA). This model is similar with the adaptive antenna system of handset supported by GloMo2 in function[6], which is practical.

According to the difference of antenna operation modes of transmitter and receiver, there are four cases between a pair of stations: omnidirectional transmission – omnidirectional receiving (o, o), omnidirectional transmission – directional receiving (o, d), directional transmission – omnidirectional receiving (d, o), directional transmission – directional receiving (d, d). The directional mode indicates directional pattern of antenna point to corresponding transmitting or receiving terminal. Four types of operation modes make the link between two nodes fall into three classes:

Class 1: (o, o);

Class 2: (o, d) and (d, o);

Class 3: (d, d).

With the same transmission power, different link modes lead to the difference of the maximum signal transmission distance. Let antenna gain be 8 dB and path loss factor be 3, the ratio of maximum signal transmission distance in three link modes is 1:1.9:3.5 (i.e., r_1: r_2: r_3=1:1.9:3.5). It follows that adaptive antennas can increase the transmission distance of signals, thus increase the connectivity of wireless networks. This is important in the multihop PRNET. However, the application of directional transmission or directional receiving mode and drastic variation of transmission distance make the medium access control (MAC) more complicated and cause another kind of hidden terminal problem. So how to design MAC protocols becomes more important. A good MAC protocol can make full use of the advantages of frequency reuse in space and improve system capacity. In following it will be discussed in detail. Adaptive antennas exchange the direction and link type information of one-hop neighbors with node controller. Let the time of antenna modes and direction switch be very short, and can be neglected.

2.2 Network Model

The network we studied is a distributed controlled, self-organized network. It can be modeled as a planar graph with a set of nodes and links, where each node has the same hardware and software and plays the same role. The network protocols have the strong ability in organizing the nodes together, which can greatly increase the robust and survivability of the packet radio networks.

A node consists of a half-duplex radio and a digital controller. All nodes work in a single channel (with the same spread sequence and frequency) and support two basic bit rates: 512/256kbps. The Low-layer protocols (MAC, LLC, Network) are implemented in the digital controller which provides for store and forward operation, relaying packets to the far nodes. MAC layer adopts non-slotted p-persistent carrier sense multiple access (P-CSMA). Packets queuing in every node is controlled by logical link control (LLC) layer. In network layer, distributed controls complete the function of route choosing, topology updating and multihop relaying and support connectionless datagrams. Mobile adaptive antenna is employed in the node. As omnidirectional mode is used, the radio provides connectivity to a number of neighboring radios. The time-overlapping packets would result in collision.

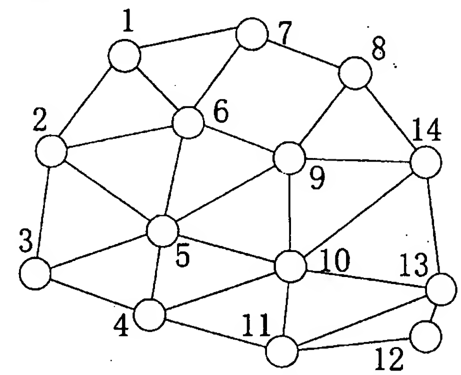

Figure 1. Network Topology

It is supposed that the node can dynamically adjust its power and spread gain. Thus the network topology may be consider stable, which is reasonable in case that the nodes hold still or move slowly. Otherwise, three types of links lead to the uncertainty of network topology structure. Figure 1 shows a network topology when nodes operate in (o, o) mode.

3. Performance Analysis

3.1 MAC Protocol

Comparing with omnidirectional antennas, the applications of adaptive antennas in PRNET give a great challenge on the design of MAC protocols. The first challenge that MAC protocols must face is how to choose transmission or receiving antenna modes between two adjacent nodes. In addition, the choices of antenna operation modes have associated with node mobility and service types. And the information of nodes location and link type also need to be collected and propagated through the whole network. More important, it is necessary to consider the cooperation of MAC protocols with other layer for realization.

The hidden terminal problem caused by mobile adaptive antennas is very different from the traditional one. In multihop PRNET, non-adjacent nodes will be

hidden from each other that bring up the dissonance of the acquired information while node is sensing channels. Consequently this increases the probability of packet collision and decreases the efficiency of network. The protocols presented in recent years, such as group allocation multiple access[9] (GAMA) and floor acquisition multiple access[10] (FAMA), multiple access collision avoidance[11] (MACA), recent IEEE802.11 standard[12] etc., try to prevent hidden terminals from simultaneous packet transmission and improve network performance. Narrow beam transmission or receiving leads to another kind of hidden terminals in the whole network. Hidden terminal problem may exist even between adjacent nodes, thus make MAC protocol based on carrier sensing lose its significance.

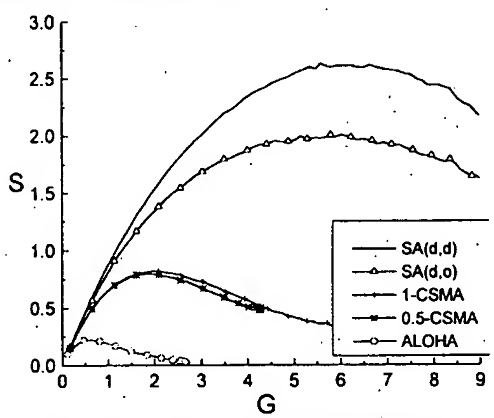

Figure 2. Comparison of Network Access Performance

Figure 2 shows the MAC protocols simulation result of the multihop PRNET in Figure 1. The G-S curve of directional ALOHA protocol adopting mobile adaptive antennas is given, and compare it with the ALOHA and p-persistent CSMA protocol adopting omnidirectional antennas. Packet generation is modeled as a Poisson process, with the source node and destination node random set. We assume the packet length is 3000 bit and channel rate is 512 kbps. In figure 2, (d, d) mode is an ideal operation mode of adaptive antennas and (d, o) mode is in common use. It is seen that mobile adaptive antennas can give significant performance enhancement only with simple directional ALOHA protocol when compared with their omnidirectional counterparts. It is due to the directional modes take advantage of the frequency reuse in space other than eliminate the effect of hidden terminals, that is to say, in directional modes several pair of nodes can transmit or receive packets in different direction without collision at the same time. In addition, application of adaptive antennas can even make $S > 1$, it is impossible to be achieved by any other current MAC protocols. Furthermore, the application of directional ALOHA protocol avoids the complex channel sensing equipment and simplifies MAC protocol design.

3.2 Network Performance Simulation

According to the network and service models in section 2, we develop a network simulation software toolkit and simulate the influence of mobile adaptive antennas on the performances of network, then compare with those of the case adopting omnidirectional antennas. Follow is the parameter definition: [13][14] :

- Every node produces packets with i. i. d. Poisson's distribution and sends them to other nodes at random. We assume that the packet-generating rate is λ and the packet length L_d is 3000 bit (L_d=3000 bit) and acknowledgement packet length is 100 bit.
- Channel transmission rate is 512 kbps.
- In MAC layer, p-persistent CSMA protocols with omnidirectional antennas and directional ALOHA protocols with adaptive antennas in (d, o) and (d, d) mode.
- Directional active acknowledgement is adopted in data link layer. The maximum number of packet retransmission is limited to 6.

- Network layer adopts the distributed Bellman-Ford (DBF) shortest path algorithm. In order to discuss the effect of directional antenna mode on network performance, we don't consider that transmission distance increases and network topology changes due to adaptive antenna gain.

Figure 3, 4 and 5 show the network performance of MAC layer adopting 0.5-persistent CSMA and 1-persistent CSMA with omnidirectional antennas and compare them with the performance of adopting mobile adaptive antennas. Three important performance measures: the average end-to-end packet delay, average packet loss rate and end-to-end network throughput are simulated. From figures we can see that after applying mobile adaptive antennas, the performances of three parameters improve greatly. These figures show the wonderful prospect of mobile adaptive antennas in multihop PRNET.

However, providing anti-noise, interference rejecting and fading mitigation, adaptive antennas can acquire better channel quality. And, the transmission distance increment after employing adaptive antenna decreases the relaying hops between source node and destination node. These can ulteriorly improve the network performance.

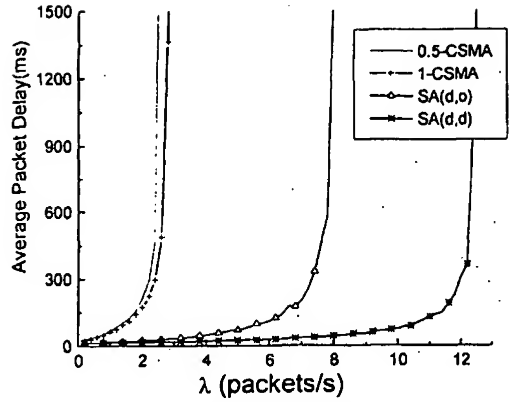

Figure 3. Average Packet Delay vs. λ

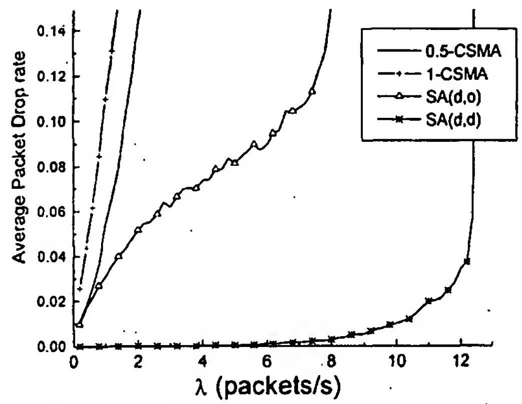

Figure 4. Average Packet Loss Rate vs. λ

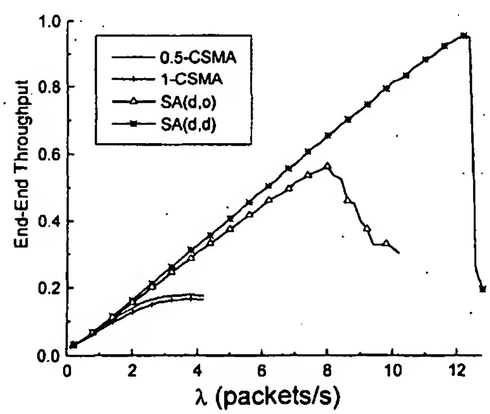

Figure 5. End-to-End Throughput vs. λ

4. Adaptive Multihop PRNET Protocols

Based on the previous simulation and analysis results, follow presents the design idea of adaptive network low-layer protocols supporting mobile adaptive antennas:

(1) Physical Layer

In physical layer, a variety of algorithms, modes and transmission or receiving controls associated with adaptive antennas are implemented. Utilizing adaptive antennas to measure the direction of arrival signals and the distance between two nodes is a new application, i.e., using adaptive antennas can detect the direction of and the distance from object node. Exchange such information with other nodes in the network, a location map of all nodes can be obtained. It is very useful for military communications. Making full use of location information, high layer can realize a variety of protocol algorithms related with location. For example, in high speed PRNET, the accuracy of distance measuring can reach within 100 meter with spread spectrum chip rate of 4.096 Mcps. Without global position system (GPS), this can also serve as an effective communication position system.

(2) MAC Layer

MAC layer adopts adaptive directional ALOHA protocol presented previously and decides which of the four transmitting and receiving antenna modes would be used according to the node location and link types. The common mode is (d, o), and the active ACK packets should be sent by (d, d). When a nodes move fast or don't obtain the location information of an adjacent node for a long time, it adopts omnidirectional ALOHA protocol (i. e., (o, o) mode) to send packets. In the case of some stream-like data services, such as voice and video, or special demands to ensure communication node pairs, (d, d) mode is used.

(3) LLC Layer

By use of mobile adaptive antennas, the conception of adjacent nodes gets to be extended. According to different transmission and receiving antenna modes, links fall into three classes. Link layer adopts directional active acknowledgment protocol, (d, d) mode is used. A link state table of adjacent nodes is created in order to update the information in time such as the types, direction and distance of links.

(4) Network Layer

The application of mobile adaptive antennas increases the network connectivity and uncertainty of topology structure, thus bring great challenge to the wireless network protocol. The design of network layer protocol should take full use of the location and link state information of nodes to realize the route algorithm in the dynamic topology.

According to the characteristics of three types of links, we constitute three route tables in the network layer with relation to three kinds of network topology structure in order to describe the state of network in detail. Some distance-vector routing algorithms should be used. Network layer can also realizes some location-aided route algorithms[15].

Another special application is so called "high-speed

information channels", where a series of nodes can setup a large scale of high-speed information channels with (d, d) mode in the busy network environment. Narrow main lobe of antennas not only eliminates the interference to receiver by most users, but also decreases the interference of transmitter to other users. It is very significant for the improvement of network performance. This technique not only provides assurable transmission in time for special services, but also supports great stream-like traffic, such as, voice, video etc., without congestion to most of other users. Design of adaptive network protocols associated with mobile adaptive antennas is a very complicated work, where the low-layer protocols are most important. The foregoing is only some ideas of low layer protocol design in adaptive multihop PRNET protocols. Detail protocols design deserves further study.

5. Conclusions

Employing adaptive antennas in mobile station is a new research direction in mobile communication area. Fortunately, recent technology activity strongly indicates that such technique would be realized in several years. Thus how to design the new protocols associated with mobile adaptive antenna becomes an urgently work. This paper presents the application of adaptive antenna technology to the mobile terminals of multihop PRNET and the analysis of its effect on network protocol. Research results show that comparing with traditional omnidirectional antenna, mobile stations adopting an adaptive antenna can greatly improve the network performance. The design ideas of adaptive network protocol are also presented.

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